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(54) **SYSTEMS AND METHODS FOR CHARACTERIZING SPATIAL DISTORTION IN 3D IMAGING SYSTEMS**

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CPC ***G06T 15/08*** (2013.01); ***A61B 6/037*** (2013.01); ***A61B 6/583*** (2013.01); ***A61B 19/52*** (2013.01); ***A61N 5/1049*** (2013.01); ***G01R 33/58*** (2013.01); ***G06T 7/0016*** (2013.01); *A61B 5/055* (2013.01); *A61B 2017/00716* (2013.01); *A61B 2017/00725* (2013.01); *A61N 2005/1052* (2013.01); *A61N 2005/1055* (2013.01); *A61N 2005/1061* (2013.01); *G06T 2207/10072* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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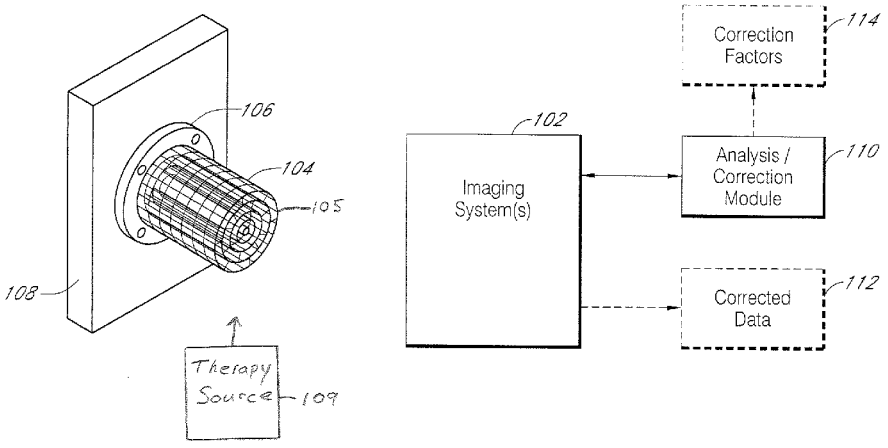
(57) **ABSTRACT**

Systems and methods for characterizing spatial distortions in location data determined by an imaging system, for example as employed in imaged guided therapy. A three dimensional phantom is custom formed for a desired imaging space of a given imaging system. The phantom includes a large plurality of control points fixed rigidly in space to a high degree of known accuracy. The phantom is fixed to a stereotactic frame defining a known calibrated reference or zero and imaged. An algorithm customized for the phantom determines the spatial locations of the control points. A comparison is made between the known and the determined spatial locations for at least a subset of the control points. The comparison results in indicia for any determined spatial distortions observed. The raw image data can be manipulated to compensate for any spatial distortion. The control points can have fixed locations known to an accuracy of 100 μm or better. The algorithm can determine an initial estimate for the detected location of a control point accurate to .+−.0.5 pixel or better.

19 Claims, 5 Drawing Sheets



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A61B 6/03	(2006.01)
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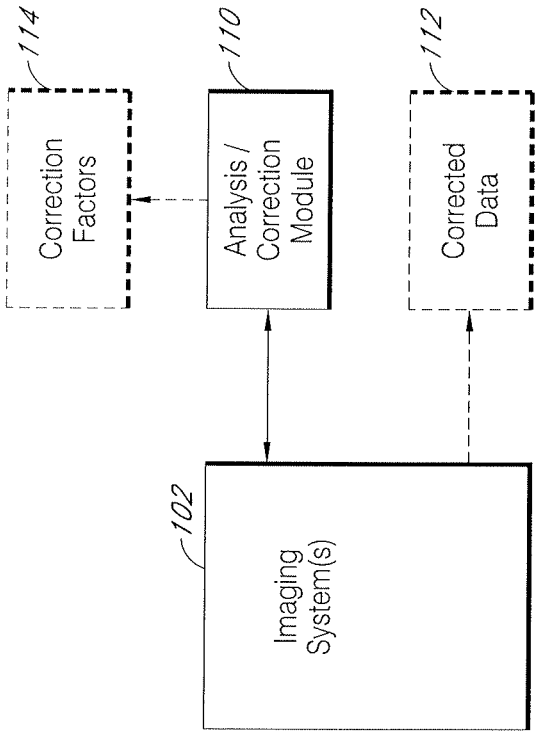
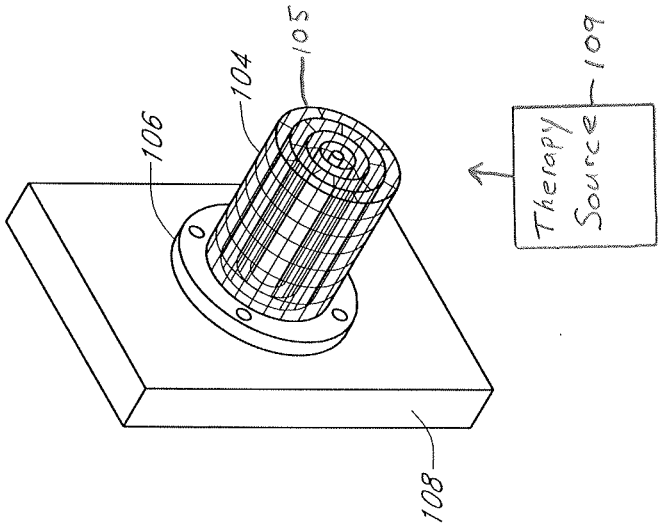

114
Correction Factors
110
Analysis / Correction Module
112
Corrected Data
102
Imaging System(s)

FIG. 1


105
104
106
109
Therapy Source
108

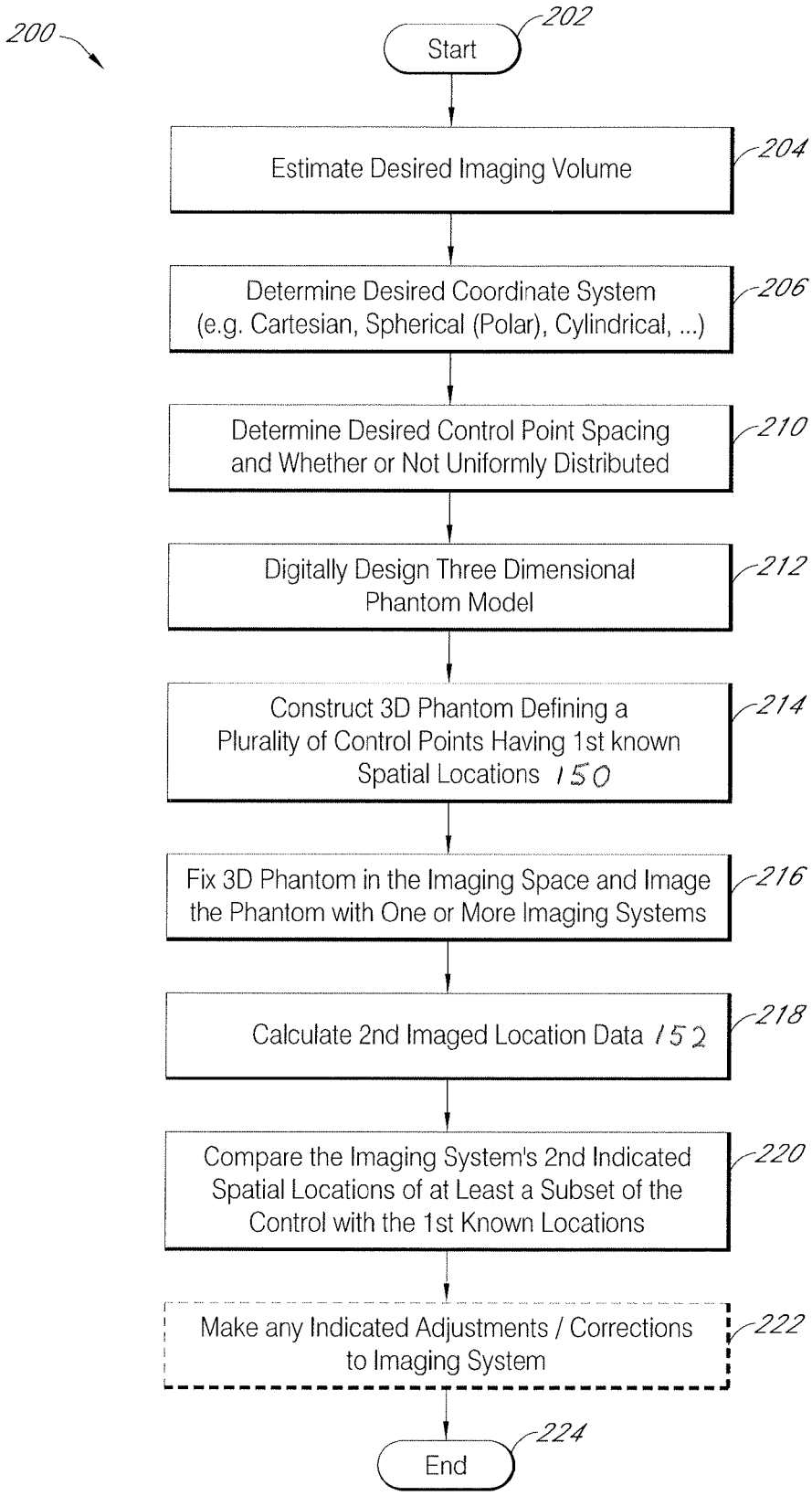

200
202
Start
Estimate Desired Imaging Volume
204
Determine Desired Coordinate System (e.g. Cartesian, Spherical (Polar), Cylindrical, ...)
206
Determine Desired Control Point Spacing and Whether or Not Uniformly Distributed
210
Digitally Design Three Dimensional Phantom Model
212
Construct 3D Phantom Defining a Plurality of Control Points Having 1st known Spatial Locations 150
214
Fix 3D Phantom in the Imaging Space and Image the Phantom with One or More Imaging Systems
216
Calculate 2nd Imaged Location Data 152
218
Compare the Imaging System's 2nd Indicated Spatial Locations of at Least a Subset of the Control with the 1st Known Locations
220
Make any Indicated Adjustments / Corrections to Imaging System
222
End
224

FIG. 2

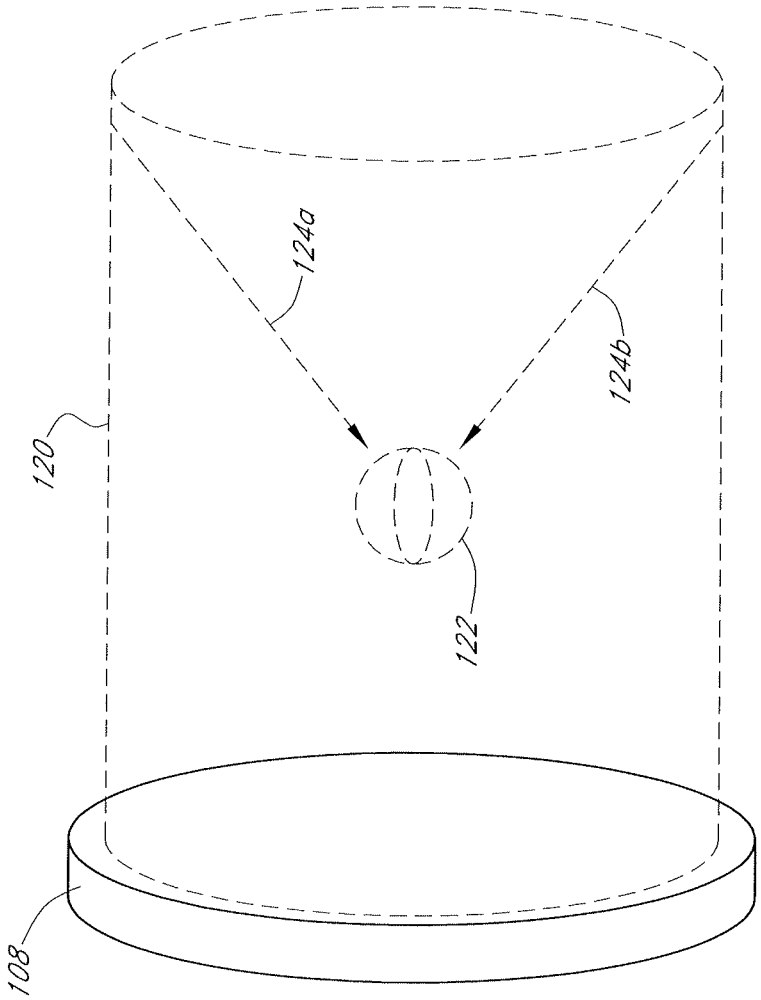


FIG. 3

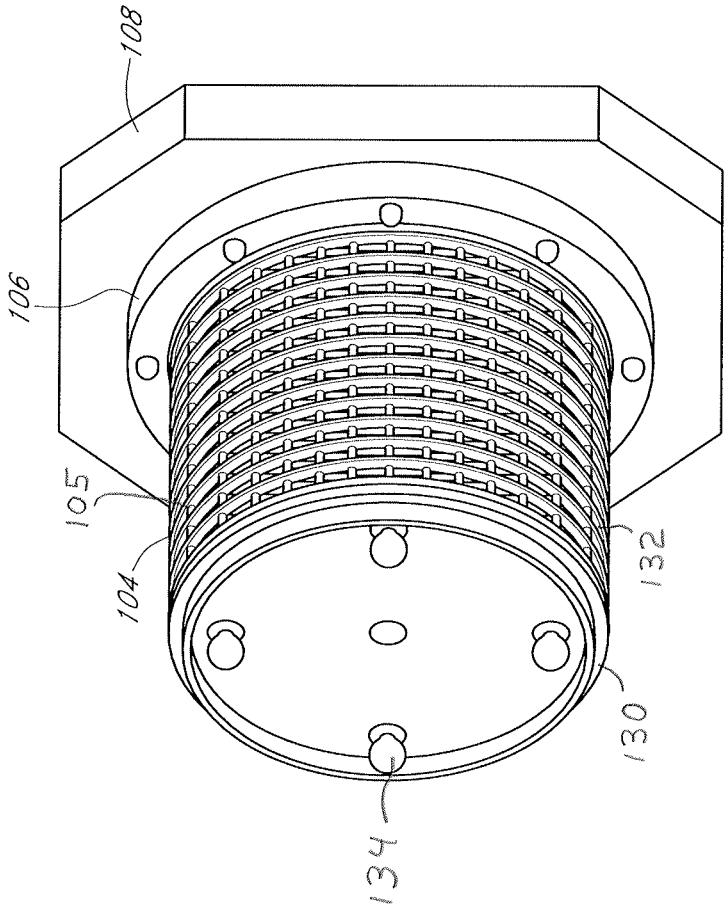


FIG. 4

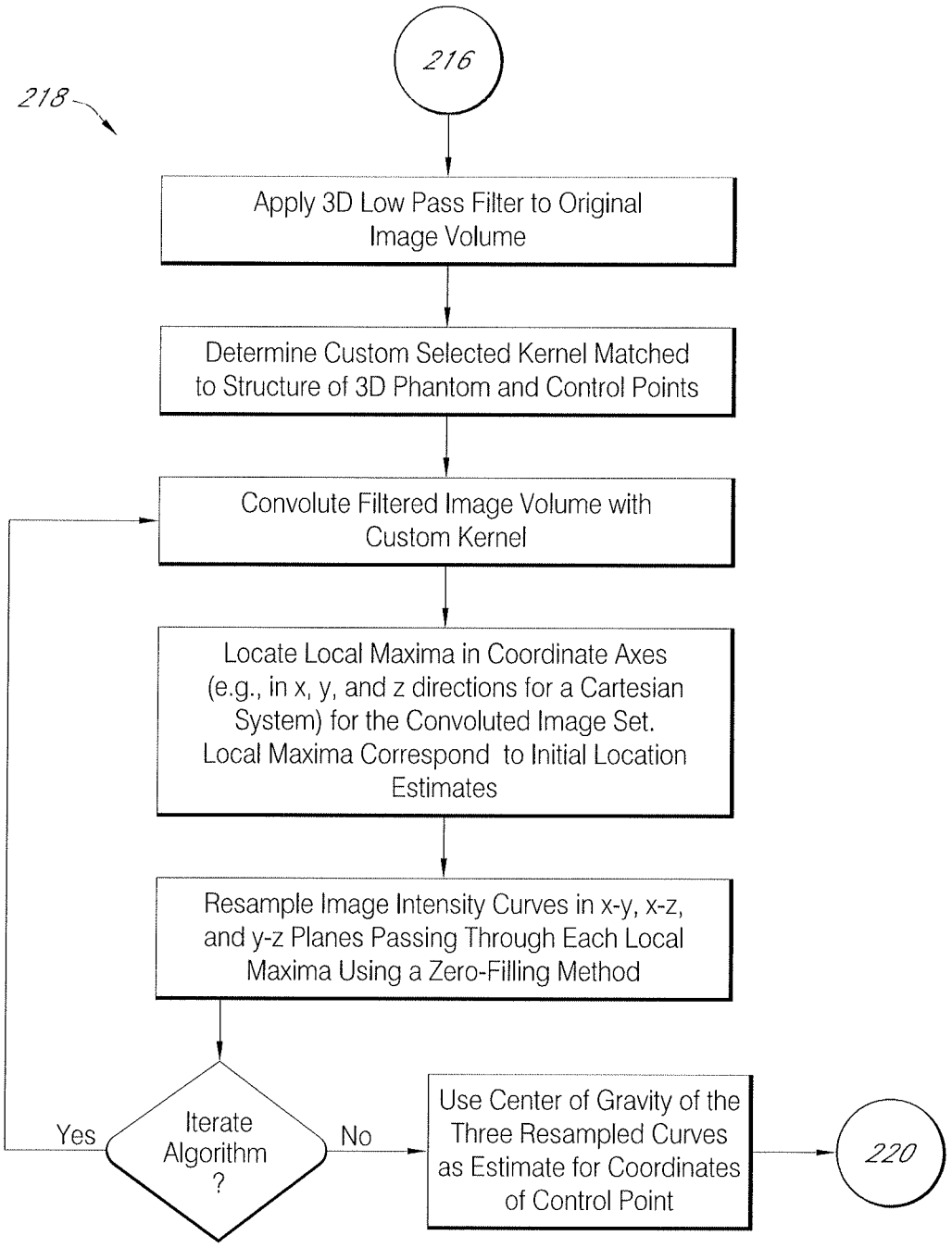

216
218
Apply 3D Low Pass Filter to Original Image Volume
Determine Custom Selected Kernel Matched to Structure of 3D Phantom and Control Points
Convolute Filtered Image Volume with Custom Kernel
Locate Local Maxima in Coordinate Axes (e.g., in x, y, and z directions for a Cartesian System) for the Convoluted Image Set. Local Maxima Correspond to Initial Location Estimates
Resample Image Intensity Curves in x-y, x-z, and y-z Planes Passing Through Each Local Maxima Using a Zero-Filling Method
Iterate Algorithm ?
Yes
No
Use Center of Gravity of the Three Resampled Curves as Estimate for Coordinates of Control Point
220

FIG. 5

SYSTEMS AND METHODS FOR CHARACTERIZING SPATIAL DISTORTION IN 3D IMAGING SYSTEMS

INCORPORATION BY REFERENCE TO ANY PRIORITY APPLICATIONS

Any and all applications for which a foreign or domestic priority claim is made are identified in the Application Data Sheet filed with the present application and are incorporated by reference under 37 CFR 1.57 and made a part of this specification.

BACKGROUND

1. Field

This disclosure relates to the field of image guided therapy and to systems and methods for creating and utilizing phantoms for characterizing imaging errors to facilitate correction of such errors.

2. Description of Related Art

Image Guided Therapies (IGT) refers to a wide range of existing and developing treatment modalities that employ one or more imaging technologies to assist more effective delivery of the related therapy. IGT can include but is not limited to such treatment modalities as image guided surgery, radiosurgery, radiotherapy, and other existing and developing types of therapy. In general, IGT utilizes one or more imaging technologies to gather information indicative of the internal structures and/or condition of tissue of interest. Image data is obtained that is generally manipulated by a computer system and associated applications software to generate and display a three dimensional virtual model or image of the imaged region. The image data can be used to more accurately locate regions of interest in space to facilitate more accurate and focused delivery of therapy to the regions of interest.

In many applications, the safety and efficacy of an IGT being used is dependent on the spatial accuracy of a 3D imaging system. For example, certain IGTs are directed to locating specific treatment regions or volumes and accurately delivering the appropriate therapy to the identified target. Errors in accurately identifying the spatial location of a desired target region can compromise the ability to accurately deliver the appropriate therapy. This can at best compromise the efficacy of the intended therapy by misdirecting the therapy and in some applications can have safety concerns, for example by unintentionally delivering the therapy to non-target regions.

A variety of imaging technologies can be used in IGT, however all known imaging technologies suffer from some degree of spatial distortion. Magnetic Resonance Imaging (MRI) utilizes a powerful magnetic field that is applied to an imaging space to preferentially align nuclear magnetization vectors, generally hydrogen atoms in water present in the tissue. Radio frequency fields are applied to alter the alignment of this magnetization thereby inducing perturbations in the magnetic field that are detectable by the MRI system. However, location data obtained via MRI systems is subject to spatial distortion from magnetic field distortions as well as chemical shifts that may occur within the imaging volume.

Computed Tomography (CT) is another type of imaging technology that utilizes computer processing to generate a virtual three dimensional image object by analyzing a generally large plurality of two dimensional x-ray images taken from different perspectives. However, CT imaging is also subject to distortion from a phenomenon known as beam hardening.

Single photon emission computed tomography (SPECT) and positron emission tomography (PET) are nuclear medicine imaging technologies that utilize radioactive tracer materials and detection of gamma rays to produce three dimensional images, frequently indicative of functional processes in the living body. In general, the tracers selected for use in SPECT systems emit gamma radiation that is detected directly whereas tracers selected for use in PET systems emit positrons which annihilate with electrons generally within a few millimeters inducing two gamma photons to be emitted and subsequently detected. SPECT and PET systems are subject to spatial distortion from such factors as attenuation and/or scatter of the gamma rays or gamma photons.

As previously noted, efficacy and safety of IGT is dependent on the accuracy of the imaging technologies used. It will thus be appreciated that there exists an ongoing need for improved systems and methods of more accurately imaging an image volume. There is also a need for characterizing spatial distortions present in an existing, or yet to be developed, imaging system.

SUMMARY

Embodiments include a method for characterizing spatial distortion of a medical imaging system, the method comprising estimating a contour and dimensions of a desired target volume, determining a desired coordinate system, determining a desired arrangement and spacing of a plurality of control points, wherein the desired arrangement and spacing is matched to the determined contour, dimensions, and coordinate system, fabricating a three dimensional phantom matched to the determined arrangement and spacing of the plurality of control points and configured to define the control points in a substantially rigid structure, fixing the phantom with respect to a stereotactic frame such that the plurality of control points defines a corresponding plurality of first known spatial locations, imaging the phantom, determining second measured spatial locations based on the imaging, comparing at least a selected subset of the first known spatial locations with corresponding second measured spatial locations, and calculating indicia of any indicated spatial distortion between the first known spatial locations and the corresponding second measured spatial locations.

Embodiments include estimating the contour and dimensions of the desired target volume is performed to match a portion of a living body.

Embodiments further include wherein the three dimensional phantom is fabricated at least in part via a rapid prototyping process.

Embodiments further include wherein the rapid prototyping process comprises selective laser sintering.

Embodiments further include operating on the second measured spatial locations so as to create a corrected set of measured spatial locations having reduced spatial distortion with respect to the first known spatial locations.

Embodiments further include fabricating the phantom such that the plurality of control points is distributed in a substantially uniform spacing.

Embodiments include a system for characterizing spatial errors in a medical imaging system, the system comprising a phantom defining a plurality of control points, wherein the control points are distributed in three dimensional space and substantially fixed with respect to each other, a fixture rigidly connectable to the phantom and connectable to a stereotactic frame of a medical imaging system such that the control points can be positioned to occupy first known spatial locations within an imaging space of the imaging system, and an

analysis module in communication with the imaging system so as to obtain data indicative of second measured spatial locations of at least a subset of the plurality of control points as determined by the imaging system and wherein the analysis module compares the first known spatial locations with the corresponding second measured spatial locations and calculates an indicia of any determined variation between the first known spatial locations and the corresponding second measured spatial locations for at least the subset of the plurality of control points.

Embodiments further include a chamber configured to enclose the phantom.

Embodiments further include wherein the chamber is configured to enclose the phantom in a substantially fluid tight manner and wherein the chamber is further provided with contrast material.

Embodiments further include wherein the analysis module further operates on the second measured spatial locations so as to create a corrected set of measured spatial locations having reduced spatial distortion with respect to the first known spatial locations.

Embodiments further include wherein the plurality of control points are distributed in a substantially uniform spacing.

Embodiments further include wherein the phantom is custom matched to the imaging system.

Embodiments further include wherein the phantom is custom matched to at least one specific imaging volume of the imaging system.

Embodiments further include storage media provided with machine executable instructions configured to induce a computer system to perform the processes of apply a three dimensional low pass filter to an original image volume resulting from an imaging operation of a three dimensional structure, determine a selected kernel matched to the three dimensional structure, convoluting the filtered image volume with the selected kernel, and locating local maxima for the convoluted image.

Embodiments further include instructions to induce the computer system to perform the process of resampling image intensity curves in multiple dimensions.

Embodiments further include instructions to induce the computer system to perform the process of making a decision whether or not to iterate previously performed processes and, if true, to iterate the processes of convoluting the filtered image volume with the selected kernel, locating local maxima for the convoluted image and resampling image intensity curves in multiple dimensions and, if not true, to perform the process of using a center of gravity of a last set of resampled intensity curves as estimates for a spatial coordinate point.

Embodiments further include instructions to induce the computer system to perform the process of comparing at least a selected subset of first known spatial locations with corresponding located local maxima and calculating indicia of any indicated spatial distortion between the first known spatial locations and the corresponding located local maxima.

Embodiments further include instructions to induce the computer system to perform the process of operating on the located local maxima so as to create a corrected set of located local maxima having reduced spatial distortion with respect to the first known spatial locations.

Embodiments include a method for characterizing spatial distortion of an imaging system, the method comprising estimating a contour and dimensions of a desired target volume, determining a desired coordinate system, determining a desired arrangement and spacing of a plurality of control points, wherein the desired arrangement and spacing is matched to the determined contour, dimensions, and coordinate system, fabricating a three dimensional phantom matched to the determined arrangement and spacing of the plurality of control points and configured to define the control points in a substantially rigid structure, fixing the phantom with respect to a stereotactic frame such that the plurality of control points defines a corresponding plurality of first known spatial locations, imaging the phantom, determining second measured spatial locations based on the imaging, comparing at least a selected subset of the first known spatial locations with corresponding second measured spatial locations, and calculating indicia of any indicated spatial distortion between the first known spatial locations and the corresponding second measured spatial locations.

Embodiments include a system for characterizing spatial errors in an imaging system, the system comprising a phantom defining a plurality of control points, wherein the control points are distributed in three dimensional space and substantially fixed with respect to each other, a fixture rigidly connectable to the phantom and connectable to a stereotactic frame of the imaging system such that the control points can be positioned to occupy first known spatial locations within an imaging space of the imaging system, and an analysis module in communication with the imaging system so as to obtain data indicative of second measured spatial locations of at least a subset of the plurality of control points as determined by the imaging system and wherein the analysis module compares the first known spatial locations with the corresponding second measured spatial locations and calculates an indicia of any determined variation between the first known spatial locations and the corresponding second measured spatial locations for at least the subset of the plurality of control points. These and other objects and advantages will become more apparent from the following description taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic illustration of one embodiment of a system for characterizing spatial distortion errors of an imaging system, for example an imaging system used in image guided therapy.

FIG. **2** is a flow chart of embodiments of characterizing spatial distortion in an imaging system.

FIG. **3** is a detailed schematic illustration of an embodiment of an imaging space or volume, for example in an image guided therapy system including a desired target region or volume and a plurality of treatment paths.

FIG. **4** is a perspective illustration of one embodiment of a high density grid phantom fixed in a stereotactic frame.

FIG. **5** is a flow chart of embodiments of a computer implemented algorithm for identifying spatial locations of control points in an image space.

DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS

FIG. **1** illustrates schematically embodiments of a system for characterizing spatial distortions that may occur in image data obtained by an imaging system **102**. The imaging system **102** can comprise one or more of a wide variety of imaging technologies including but not limited to MRI, CT, SPECT, and PET. The imaging system **102** can passively monitor one or more types of emissions from an imaging volume or space. The imaging systems **102** may also generate or project fields, energies, and/or particles and monitor interactions of these projected or generated energies and/or particles with the imaged volume.

As previously noted, known imaging systems **102** are subject to at least some degree of spatial distortion. In at least some applications, the spatial distortion is at least in part generally repeatable and can be referred to as machine dependent distortion. Such distortion is generally dependent on the design and construction of a given imaging system **102** and the nature of the imaging modality. In some applications, spatial distortion can also be dependent, at least in part, on the physical characteristics of materials being imaged. In some known imaging systems **102**, the spatial distortion can result in discrepancies between the true location of a given point from its measured spatial location as determined by the imaging system **102**. The spatial distortion normally varies for individual imaging systems **102**, however can commonly range in magnitude from on the order of several millimeters to several centimeters in error. Embodiments described herein facilitate accurate identification or characterization of such errors at a large plurality of control points within an imaging volume and facilitate correction of any distortions or errors to assist more accurate delivery of image guided therapies.

The system comprises a three dimensional or 3D phantom **104**. The phantom **104** comprises material that is specifically selected to be distinguished by an associated imaging system **102** from surrounding material. The 3D phantom **104** can comprise a three dimensionally extending grid or frame structure comprising a plurality of interconnected solid elongate members. The connection or intersection of adjoining elongate members defines a plurality of control points **105** which are spatially distributed in three dimensions. Individual elongate members can be considered as posts or struts. The individual elongate members can be substantially straight or can define a curved structure. A combination of substantially straight and of curved members is possible.

In some embodiments, a 3D phantom **104** is formed from hollow elements which can be filled with fluid containing contrast agent or radioactive material that can be readily distinguished by an associated imaging system **102** from surrounding material. The connection or intersection of these fluid columns defines a plurality of control points **105** which are spatially distributed in three dimensions. The individual hollow elongate members can be substantially straight or can define a curved structure. A combination of substantially straight and of curved members is possible.

The 3D phantom **104** is a substantially rigid structure and thus the control points **105** are substantially maintained in a fixed time invariant spatial location with respect to each other. This allows the 3D phantom **104** to maintain a large plurality of control points **105** distributed in three dimensions and having a spatial location knowable to within a high degree of accuracy. In some embodiments, the spatial location of a given control point **105** is known accurate to within approximately 0.1 mm or 100 μm or better. In some embodiments, the 3D phantom **104** maintains the control points **105** to within a known accuracy of 0.06 mm or 60 μm or better. In general, a higher degree of known spatial location accuracy is preferable, however various levels of accuracy can be indicated, based on speed and cost concerns and the accuracy requirements for a given IGT.

In some embodiments, a 3D phantom **104** is formed to correspond generally to the contours and dimensions of a desired image space or volume **120** (see FIG. **3**). The image space or volume **120** corresponds generally to a volume of space from which the imaging system **102** will obtain measurements and create a virtual image from. In many applications, the image space or volume **120** will be fixed with respect to a stereotactic frame **108**. The configuration and size of a 3D phantom **104** can be matched to the image space or volume **120** of interest.

In some embodiments, a 3D phantom **104** can comprise a three dimensionally extending grid that is formed around an incorporated internal volume that models or replicates anatomical structures and/or implants known to produce subject dependent imaging distortions. For example, sinuses containing air can create distortions in MR based imaging of the brain. By assessing distortion due to anatomical structures and/or implants, significant improvements in the accuracy of image guided treatments can be provided for individual patients.

For example, image guided therapy is frequently utilized for localized treatment of a particular portion of the living body, for example a region of interest within a patient's head. Accordingly, in at least some applications, an imaging system **102** need not and may not develop image data of the entire living body. Accordingly, the 3D phantom **104** can be configured and sized to correspond generally to the region of interest. While FIG. **1** illustrates an embodiment of 3D phantom **104** having a generally cylindrical contour or shape, this is simply illustrative of one embodiment. In other embodiments, a 3D phantom **104** can have other shapes or contours including but not limited to spheres, cubes, rectangular prisms, triangular prisms, and other geometric shapes. In yet other embodiments, the 3D phantom **104** can describe irregular geometries, for example an anthropomorphic contour. Other shapes and contours are possible.

In various embodiments, a given imaging system **102** may employ or be capable of employing one or multiple coordinate systems in developing the virtual image generated by the imaging system **102**. For example, a given imaging system **102** may employ Cartesian coordinates, spherical or polar coordinates, and/or cylindrical coordinates. Accordingly, in at least some applications, the 3D phantom **104** is preferably constructed such that the control points **105** are spatially oriented and matched in such a manner as to cooperate with the particular coordinate system(s) used by an associated imaging system **102**. Thus, in various embodiments, the 3D phantom **104** can have the control points **105** positioned generally along orthogonal or Cartesian axes, polar or spherical axes, or cylindrical axes.

Depending on the needs of a given application, the individual control points **105** can be generally uniformly distributed within the 3D phantom **104** or can be distributed in a wide variety of non-uniform distributions. In one non-limiting embodiment, a 3D phantom **104** comprises a plurality of control points **105** arranged in a substantially uniform distribution and having a point to point spacing for the control points **105** of approximately 8 mm. This embodiment can comprise a 3D phantom **104** formed of polyamide. Such an embodiment has been found particularly effective in characterizing spatial distortions in imaging systems **102** comprising MRI technologies.

As previously noted, an imaging system **102** is frequently utilized in combination with a stereotactic frame **108**. The stereotactic frame **108** generally maintains a substantially fixed rigid spatial reference or origin that can be maintained during both an imaging process and a treatment process. For example, in some embodiments a stereotactic frame **108** can comprise a stereotactic halo configured to maintain a patient's head in a relatively fixed immobile location. In one embodiment, a fixture **106** is included that can be rigidly connected to the phantom **104** and to the stereotactic frame **108**. In some embodiments, connection of the fixture **106** to the phantom **104** is substantially permanent and in other

embodiments the connection can be removable or detachable. In at least some applications, it will be generally preferred that the rigid connection between the fixture **106** and the stereotactic frame **108** be removable. This aspect provides the advantage of rigidly fixing the 3D phantom **104** with respect to the stereotactic frame **108**, however in a temporary or removable manner. This facilitates utilization of the same stereotactic frame **108** for imaging the 3D phantom **104** as well as for delivery of therapy, such as from a therapy source **109**.

As previously noted, a given imaging system **102** is generally subject to at least some degree of spatial distortion when developing image data from an image space or volume **120**. By imaging one or more embodiments of 3D phantom **104**, the imaging system **102** can develop measured location data, for example of the plurality of control points **105**. This measured location data can be compared with the known location of the control points **105**, as the 3D phantom **104** comprises a substantially rigid structure which is rigidly connected to a stereotactic frame **108** defining a known spatial reference or zero.

In one embodiment, image data obtained by an imaging system **102** can be communicated to an analysis module **110**. The analysis module **110** can comprise machine executable code stored on computer readable storage media, wherein the code is configured to induce a computer system to perform the actions described for one or more of the embodiments described herein. The analysis module **110** can be provided with the known location data of the plurality of control points **105** of the 3D phantom **104**. Thus, the known location of a given control point **105** can comprise a first known spatial location **150** (FIG. **2**). The measured spatial location of the same control point **105** as determined by the imaging system **102** can comprise a second measured or imaged spatial location **152** (FIG. **2**). The analysis module **110** can be configured to compare the first known spatial location **150** with the second measured spatial location **152** for each of a plurality of control points **105** and use this comparison to characterize any spatial distortion indicated by the comparison.

By employing computer processing and associated applications software and memory, the analysis module **110** can rapidly characterize any spatial distortion between the first and second spatial locations **150**, **152** for a large plurality of control points **105** distributed within an image space **120**. Depending on the requirements of a given application, the analysis module **110** can analyze all or substantially all of the control points **105** comprising the 3D phantom **104**. In some applications, the analysis module **110** may analyze only a selected subset of the total plurality of control points **105**. It will be understood that the particular boundaries/parameters of a selected subset of the control points **105** can be selected based on the needs and requirements of a particular application.

In some embodiments, communication between the imaging system **102** and analysis module **110** is bidirectional. In such embodiments, the analysis module **110** can be further configured to provide correction information to accommodate and correct for any identified spatial distortions. Thus, in some embodiments, an analysis/correction module **110** can obtain image data from the imaging system **102**, analyze this data for any indicated spatial distortions, and provide return data and/or commands to the imaging system **102**. Thus, in some embodiments, the imaging system **102** can provide corrected data **112** in cooperation with an analysis/correction module **110**.

It will be understood that in some embodiments, an analysis/correction module **110** can be physically integrated with the imaging system **102**. In some embodiments, an analysis/correction module **110** can be materially separate but in communication with an imaging system **102**. It will be further understood that the operation of the analysis/correction module **110** need not be concurrent with generation of or communication of image data from the imaging system **102**. Thus, the analysis and correction processes performed by various embodiments as described herein can be performed offline with respect to operation of the imaging system **102** or can occur at least in part concurrently therewith. In some embodiments, analysis of any spatial distortions occurs substantially concurrently or in parallel with generation of the image data.

In some embodiments, communication between an imaging system **102** and an analysis/correction module **110** can be unidirectional from the imaging system **102** to the analysis/correction module **110**. Thus, in some embodiments, the corrected data **112** can be obtained from the analysis/correction module **110** but not necessarily provided to the imaging system **102** itself. Thus, the corrected data **112** can be provided for use by a clinician or other user while the imaging system **102** provides only "raw data" or data including the spatial distortion.

In yet other embodiments, an analysis module **110** may provide only analysis of any spatial distortions present in a given imaging system **102**. For example, in some embodiments, an analysis module **110** can generate and communicate correction factors **114** indicative of the magnitude and direction of any discrepancies between the first known spatial location **150** and second measured or imaged spatial location **152** of one or more control points **105**. The correction factors **114** can be utilized by a clinician or other users or other computer based systems based on the needs of a given application. Thus, in at least some embodiments, neither an imaging system **102** nor an analysis module **110** need necessarily provide final corrected image data **112** of the image space **120**.

FIG. **2** illustrates a flow chart of embodiments of methods of characterizing spatial distortion in an imaging system. The method **200** begins in a start block **202** which generally describes installation and initial calibration of the imaging system **102** and the stereotactic frame **108**. The start block **202** can include calibration or orientation of the stereotactic frame **108** so as to accurately define a spatial reference or zero.

In a block **204**, a desired imaging volume **120** is estimated. Block **204** can include establishing the general contour and dimensions of the desired imaging volume **120**. In a block **206**, the desired coordinate system is determined. The determination of the desired coordinate system in block **206** is frequently dependent on the characteristics and design of the associated imaging system **102**. In many applications, Cartesian coordinates are widely used and understood by clinicians and other users, however spherical and cylindrical coordinate systems can also be used.

In a block **210**, a determination is made of the desired control point spacing. A desired spacing between individual control points **105** can vary based on the imaging technology of an associated imaging system **102** as well as the particular operating parameters thereof. Desirable control points **105** spacing can also vary depending on the material characteristics of the patient tissue to be subsequently imaged. Block **210** also includes a determination of whether or not the control points **105** are desirably spaced substantially uniformly or non-uniformly. For example, in some applications, an image space **120** defined by the imaging system **102** may be substantially larger than an actual region or volume of interest, for example a treatment volume or region **122** (FIG. **3**). Thus,

in at least some applications, it can be more efficient and timely to distribute control points **105** in a non-uniform manner. For example, control points **105** may be more closely spaced in a portion of an overall image space **120** to obtain more accurate characterization of spatial distortions within a smaller region of interest **122** within a larger image space **120**. This can simplify construction of a 3D phantom **104** and reduce processing overhead required to characterize the spatial distortion in regions of less interest.

In a block **212**, a three dimensional model of the 3D phantom **104** is created. Block **212** can include use of digital design tools such as computed aided design (CAD)/computer aided manufacturing (CAM).

In a block **212**, the 3D phantom **104** is constructed based on the three dimensional model developed in block **212** so as to define the selected plurality of control points **105** having first known spatial locations and relationships. In one embodiment, block **214** employs one or more rapid prototyping technologies, for example selective laser sintering (SLS).

In one embodiment, block **214** employs an additive manufacturing technique utilizing a high power laser to selectively fuse relatively small particles or powders of polyamide plastic in a spatially highly accurately controlled manner. In one embodiment, block **214** selectively fuses powdered polyamide by sequentially scanning cross-sections of a bed of powdered polyamide according to the contours and dimensions of the 3D phantom model developed in block **212**. As each cross-section is scanned, the powder polyamide fuses to form a layer or level of the 3D phantom **104**. Additional polyamide powder can be added with each scanning cross-section and the 3D phantom **104** is constructed in a bottom-up or end-to-end manner.

The combination of a selective laser sintering process based on the accurate three dimensional model developed in block **212** results in a 3D phantom **104** having highly accurate placement of a large plurality of control points **105**. As previously noted, in some embodiments the control points **105** are located with an accuracy of 100 μm or more. In some embodiments, the control points **105** are located with an accuracy of 60 μm or less. In other embodiments, other rapid prototyping technologies including but not limited to fused deposition modeling (FDM) and/or serial lithography (SLA) can be utilized. It will be further understood that the 3D phantom **104** comprising polyamide is simply one, non limiting example and other embodiments can employ other materials in addition to or as an alternative to the previously described polyamide, depending on the needs of a given application.

In a block **216**, the 3D phantom **104** is fixed in the imaging space **120**, for example via attachment of the fixture **106** to the 3D phantom **104** and the stereotactic frame **108**. Since the stereotactic frame **108** defines a known and calibrated spatial reference or zero and since the relative locations of the control points **105** are also fixed and known, the true spatial locations of each individual control point **105** is known to a high degree of accuracy. Block **216** also includes imaging the 3D phantom **104** with one or more imaging systems **102** to obtain the second measured or imaged location data **152**.

In a block **218** a computer implemented algorithm is employed for automated detection of phantom control points **105** in the image space **120**. As previously noted, an apparatus employing embodiments of the method **200** can comprise machine executable code stored on computer readable storage media and configured to induce the computer to perform the processes described herein.

In block **218**, a 3D low pass filter is applied to the original image volume. A convolution kernel is determined and used that is specifically designed to match the structure of the grid intersections that form the control points **105**. The convolution kernel is thus customized for a each phantom **104** geometry and size. For embodiments comprising rectangular grid arrays formed by rectilinearly arranged posts and struts, the kernel preferably used has the general shape of a three-dimensional plus sign. Other kernels can be selected and used for other configurations of the control points **105**. The purpose of the convolution is to increase the intensity of the pixels in the intersection points of the image. The intersections after the convolution are about fifty percent brighter than the surrounding grid.

Local maxima of the control points **105** are then found for the convolved image set in the x, y, and z directions. Finding these maxima provides an initial estimate for coordinates of the grid intersections, e.g. the spatial location of the respective control points **105**, to an accuracy of .±.0.5 pixel or greater. To refine the estimate, the image intensity curves in the x-y, x-z, and y-z planes passing through each local maximum are resampled using a zero-filling method. The center of gravity for the three resampled curves is used as a new estimate for the coordinates of the grid intersection.

The accuracy of these embodiments for identifying the measured second coordinates for the plurality of control points **105** has been experimentally determined by comparing distances derived from the embodiments of automated detection routine described herein with measurements obtained using a high accuracy caliper. The degree of accuracy obtained was an unexpected positive result.

In a block **220**, a comparison is made between the imaging system's second indicated or measured spatial locations with the first known spatial locations of at least a subset of the control points **105**. Block **220** can return a magnitude and direction of any detected distortion resolved into each of three dimensions in the appropriate coordinate system. Block **220** can also return a magnitude and direction of any detected distortion as a distortion vector in the appropriate coordinate system. Block **220** can return results as a plurality of individual spatial distortion indicia. Block **220** can also return results as one or more composite or generalized distortion indicia for a plurality of individual spatial distortions.

In a block **222**, any indicated adjustments or corrections can be made to the raw image data from the image system **102** to result in corrected or normalized image data **112**. As previously noted, this correction of block **222** can be performed by an analysis/correction module **110**, by the imaging system **102**, or by a separate component or process. Due to the large plurality of control points **105** and corresponding large amount of possible spatial distortion data, it is generally strongly preferred that the calculations and corrections described herein be performed via a computer implemented process.

FIG. **3** illustrates schematically one embodiment of an image space or volume **120** in greater detail. As previously described, a stereotactic frame **108** defines a spatial reference or zero for location measurements made in the image space **120**. In this embodiment, a subset or smaller region **122** within the image space **120** is of increased interest to the user. In one embodiment, the subset or smaller region corresponds to a treatment space **122** forming a subset or smaller region of the larger overall image space **120**. The treatment space **122** can spatially correspond to a future target location for any of a variety of treatment modalities from the treatment source **109**. Treatment can include one or more of accelerated proton therapy, ionizing radiation, infrared radiation, laser, and the like. FIG. **3** also illustrates a first and second treatment path **124***a*, **124***b* intersecting the treatment space **122** and indicat-

ing schematically deliver of the therapy via different spatial approaches. Thus, embodiments can provide characterization of spatial distortion not only of a treatment space or volume **122** of interest within the image space **120**, but also one or more treatment paths **124** traversing the image space **120**.

FIG. **4** illustrates in greater detail one embodiment of a 3D phantom **104** rigidly attached to a fixture **106** and thus to a fixed stereotactic frame **108**. In some embodiments, materials comprising the phantom **104** can be invisible to at least some implementations of imaging system **102**. For example, polyamide material is generally invisible to MRI, SPECT, and PET based imaging systems **102**.

Thus, one embodiment further comprises a chamber **130** configured to enclose the phantom **104**. The chamber **130** shown transparent in FIG. **4** to facilitate viewing of the phantom **104**, however is configured to enclose the phantom **104** in a fluid tight manner. The chamber **130** is preferably filled with a contrast material **132** that is visible to the image system **102**. The contrast material **132** can comprise copper sulfate solution or mineral oil for MRI based imaging systems **102**. The contrast material **132** can comprise gamma or positron emitting substance for SPECT or PET based imaging systems **102**. The contrast material **132** allows the imaging system **102** to "see" the boundaries of the phantom **104** and the visible contrast material **132** and thereby identify the location of the control points **105** in the image space **120**.

In one embodiment the chamber **130** further comprises one or more access ports **134**. The access ports **134** provide access for introducing the contrast material **132**. The access ports also facilitate clearing trapped air/bubbles from the chamber **130**. The access ports **134** also provide access to the phantom **104** when it is desired to verify the location of the grid control points **105** with respect to the stereotactic frame **108**.

For example, in frame-based image guided treatments (which are the most accurate form of image guided therapy), both image and treatment spaces are referenced to the stereotactic frame **108**. It can be preferred to express the location of the any spatial distortions identified with the phantom **104** in reference to this same stereotactic frame **108**. In practice, once the phantom **104** is placed in the chamber **130**, the chamber **130** is securely attached to the stereotactic frame **108**. The system can access a metrology lab to precisely measure the grid position of the control points **105** with respect to the stereotactic frame **108** fiducials. The fiducials can vary for a specific implementation of stereotactic frame **108**, however can be considered as a coordinate system for the stereotactic frame **108**.

Suitable materials and processing methods to form the 3D phantom **104** with the degree of spatial accuracy obtainable according to the embodiments described herein has not previously been available. Appropriate algorithms to analyze the resulting large amount of data obtained against a corresponding large amount of reference data have also not been available. The problems of spatial distortion have existed, but a suitable solution has previously proven elusive. Previous attempts have been incapable of providing the degree of precision and specificity for a given application as the disclosed embodiments. While reference has been made to imaging systems **102** in the context of image guided therapy, it will be understood that embodiments described and illustrated herein can be advantageously employed in any of a wide variety of imaging systems.

Although certain embodiments of the present disclosure have shown, described and pointed out certain novel features as applied to those embodiments, it will be understood that various omissions, substitutions and changes in the form of the detail of the device illustrated may be made by those skilled in the art without departing from the spirit of the invention. Consequently, the scope of the invention should not be limited to the foregoing description but is to be defined by the appended claims.

The following is claimed:

1. A method for characterizing spatial distortion of a medical imaging system, the method comprising:

estimating a contour and dimensions of a desired target volume;

determining a desired coordinate system;

determining a volumetric arrangement and uniform spacing of a plurality of control points in a three-dimensional space, wherein the desired arrangement and spacing is matched to the contour, dimensions, and coordinate system such that the control points are interspersed within and throughout the entire target volume;

providing a substantially rigid three-dimensional phantom that is matched to the determined volumetric arrangement and uniform spacing of the plurality of control points in the three-dimensional space and that is also configured to rigidly fix the control points in an interspersed manner throughout its substantially rigid structure;

fixing the phantom with respect to a stereotactic frame such that the plurality of control points defines a corresponding plurality of first known spatial locations;

imaging the phantom;

determining second measured spatial locations based on the imaging;

comparing at least a selected volumetric subset of the first known spatial locations with corresponding second measured spatial locations; and

calculating indicia of any indicated volumetric spatial distortion between the first known spatial locations and the corresponding second measured spatial locations.

2. The method of claim **1**, wherein the estimating the contour and dimensions of the desired target volume is performed to match a portion of a living body.

3. The method of claim **1**, wherein the three dimensional phantom is fabricated at least in part via a rapid prototyping process.

4. The method of claim **3**, wherein the rapid prototyping process comprises selective laser sintering.

5. The method of claim **1**, further comprising operating on the second measured spatial locations so as to create a corrected set of measured spatial locations having reduced spatial distortion with respect to the first known spatial locations.

6. A system for characterizing spatial errors in a medical imaging system, the system comprising:

a substantially rigid three-dimensional phantom having a plurality of control points, wherein the control points are interspersed uniformly within and throughout a three-dimensional volume and are substantially rigidly fixed with respect to each other;

a fixture rigidly connectable to the phantom and connectable to a stereotactic frame of a medical imaging system such that the control points can be positioned to occupy first known spatial locations within an imaging space of the imaging system; and

an analysis module in communication with the imaging system so as to obtain data indicative of second measured spatial locations of at least a volumetric subset of the plurality of control points as determined by the imaging system and wherein the analysis module compares the first known spatial locations with the corresponding second measured spatial locations and calculates an indicia of any determined variation between the first

known spatial locations and the corresponding second measured spatial locations for at least the volumetric subset of the plurality of control points.

7. The system of claim **6**, further comprising a chamber configured to enclose the phantom.

8. The system of claim **7**, wherein the chamber is configured to enclose the phantom in a substantially fluid tight manner and wherein the chamber is further provided with contrast material.

9. The system of claim **6**, wherein the analysis module further operates on the second measured spatial locations so as to create a corrected set of measured spatial locations having reduced spatial distortion with respect to the first known spatial locations.

10. The system of claim **6**, wherein the plurality of control points are distributed in a substantially uniform spacing within a sub-volume of the phantom corresponding to a planned treatment volume.

11. The system of claim **6**, wherein the phantom is custom matched to the imaging system.

12. The system of claim **11**, wherein the phantom is custom matched to at least one specific imaging volume of the imaging system.

13. An apparatus for characterizing volumetric spatial distortion of a medical imaging system, the apparatus comprising:

a substantially rigid volumetric phantom comprising:

a three-dimensional volume;

an outer perimeter generally enclosing the three-dimensional volume;

a plurality of control points that are interspersed uniformly within the outer perimeter and throughout the three-dimensional volume and that are substantially rigidly fixed with respect to each other and with respect to the outer perimeter;

a fixture configured to rigidly fix the phantom to a spatial reference point such that the control points occupy known spatial locations within an imaging space of the imaging system; and

an analysis module configured to:

communicate with the imaging system to obtain measured spatial locations of at least a volumetric subset of the plurality of control points as determined by the imaging system;

compare the known spatial locations with the corresponding measured spatial locations as determined by the imaging system; and

calculate any determined variation between the known spatial locations and the corresponding measured spatial locations for at least the volumetric subset of the plurality of control points.

14. The apparatus of claim **13**, further configured to use indicia of the determined variation to apply a correction factor, thereby correcting for volumetric spatial distortion of the imaging system.

15. The apparatus of claim **13**, wherein the plurality of control points comprise intersections of elongate rigid material.

16. The apparatus of claim **13**, wherein the three-dimensional volume has numerous control points volumetrically spaced and thereby configured to be imaged from any of a plurality of angles, the angles corresponding to treatment angles.

17. The apparatus of claim **16**, wherein the control points are spaced and configured to allow for effective calibration of a proton beam therapy system having high resolution treatment capabilities.

18. The apparatus of claim **13**, wherein the outer perimeter is generally cylindrical, the control points are interspersed in bands exhibiting cylindrical symmetry, and bands of successively wider radius have control points that are spaced farther from each other than in the previous band.

19. The apparatus of claim **13**, wherein the control points have one point to point spacing in a target subvolume and a different point to point spacing outside the target subvolume but still within the three-dimensional volume and the outer perimeter thereof.

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